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Electrical power generation from ocean currents in the Straits of Florida: Some environmental considerations

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ABSTRACT

Ocean currents contain a remarkable amount of kinetic energy and have potential worldwide capability. Initial tests to harness current power focus on the Straits of Florida where the Florida Current has a total flow capacity of about 30×10^6 m^3 s^{-1}. Generation of clean electricity from ocean currents off southeast Florida is based on a power extractor comprising open-center turbine technology. This innovative turbine provides safe passage for fish and other aquatic species. The water-column array of energy production units (EPUs) will have a 350 km^2 footprint, based on a 600 m (10 rotor diameters) downstream separation distance between EPUs with a lateral separation of 400 m. Water depths for the EPU field are in the range of 100–500 m. With such a large area of water column and benthic habitat utilized, environmental concerns must be overcome, including routing of transmission lines to shore. Risks and vulnerabilities of the proposed ocean current generated electricity include failure of individual EPUs and damage to sensitive coastal marine environments during installation.

Contents

1. Introduction

The ocean holds such vast amounts of energy that it is hard to quantify the potential [1]. Energy is available in many different forms [2–5] including wind, wave, (tidal) current, thermal, geothermal, solar, salinity gradients, biomass, and methane hydrates to name a few. Recent efforts (Table 1) are initiating focus on offshore activities to develop sustainable energy sources for the future of modern civilization. Table 1 summarizes some examples of efforts by corporate and governmental entities to harness some of the power of the oceans. Although this list is not inclusive, it gives an impression of the international effort that is being given to ocean energy development. The United States is only now beginning to place importance on sustainable and renewable energy resources. Ocean currents, one of the largest untapped renewable energy resources on the planet, show a global potential of over 450,000 MW (450 GW) and representing a market of more than US$550 billion.

The massive oceanic surface currents of the world are untapped reservoirs of energy. Because of their link to winds and surface heating processes, the ocean currents are considered as indirect sources of solar energy. Areas with high marine current flows commonly occur in narrow straits, between islands, and around

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Table 1
Examples of ocean energy developers and installations in North America and Europe, by country and research institution of corporate enterprise. The type of ocean power under development is indicated in parentheses. (Modified from Practical Ocean Energy Management Systems, Inc., POEMS, http://www.poemsinc.org/links.html and from Finkl, Charlier, and Hague, 2005.).

North America - USA
374's Electric Power Corporation (ocean surf energy systems), Stoughton, MA
ABS Alaskan (turbines for current, tidal, OWC energy), Fairbanks, AK
Aqua Energy Group, Ltd. (offshore wave energy), Mercer Island, WA
Cape Wind (offshore wind energy) Cape Cod, MA
DEKA Research & Development Corporation (salinity energy/water desalination), Manchester, NH
Elemental Innovation, Inc. (floating breakwaters, offshore wave energy), West Caldwell, NJ
Float Incorporated (offshore wave energy), San Diego, CA
Florida Hydro Power and Light Company (offshore Gulf Stream current energy), Palatka, FL
GCK Technology, Inc. (Gorlov Helical Turbines), San Antonio, TX
Gamell Power (compressed air from waves/bladeless turbines/water vortices), San Clemente, CA
Hawaii Energy Department (OTEC energy), Honolulu, HI
HydroVenturi (tidal energy), San Francisco, CA
Independent Natural Resources, Inc. (INRI) (shoreline wave energy), Edina, MN
Kinetic Energy Systems (tidal current energy), Ocala, FL
Marine Development Associates, Inc. (OTEC), Saratoga, CA
Marine Innovation & Technology (ocean energy systems), Berkeley, CA
Mo-T.O.P.S Oceanic Power Systems (OTEC variant), Del Rio, TX
OCEES, International Ocean Engineering and Energy Systems (OTEC), Honolulu, HI
Ocean Power Technologies, Inc. (Near Shore Wave Energy), West Trenton, NJ
Ocean Wave Energy Company (Off Shore Wave Energy with onshore component), Bristol, RI
Ocean Swell Momentum Electricity Generating System - Hull Encapsulated Wave Energy, San Francisco, CA
Ocenergy- Near Shore, Offshore Wave Energy, CT
Quantum Energy Solutions - Near Shore Wave Energy, WA
Renergy Pacific Corporation- Near Shore Wave Energy, San Diego, CA
SARA Inc- Near Shore Wave Energ y, Huntington Beach, CA
Sea Solar Power-OTEC Energy, Baltimore, MD
SeaVolt Technologies (near shore wave energy), Berkeley, CA
Solomon Technologies (off shore wave energy, electric propulsion), Benedict, MD
Tidal Electric, Inc. (nearshore tidal energy), West Simsbury, CT and Anchorage, AK
UEK Corporation (turbines for current, tidal, OWC energy), Annapolis, MD
Verdant Power (tidal current energy), East River, NY
Wader LLC (salinity gradient energy), Laguna Beach, CA
Webb Research Corporation, Slocum Glider (heat engine based on ocean thermocline energy), E. Falmouth, MA
Wave Dispersion Technologies, Inc. (WhisprWave floating breakwaters; wave attenuation-port security), Summit, NJ
Winergy LLC (offshore wind energy), Shirley, NY
North America - Canada
Blue Energy Canada (turbines for current, tidal, OWC energy), Alberta
Brooke Ocean Technology (moored wave-powered profiler), Nova Scotia
Sea Breeze Power Corp. ("Run of River" hydro projects and utility scale offshore wind farms), Vancouver, B.C.
Wavemill Energy Corp. (nearshore wave energy), Canada
Europe
Denmark
Wave Energy (offshore, nearshore wave energy)
WaveDragon (offshore wave energy), København
WavePlane International A/S (offshore wave energy), Denmark (New Jersey Rep)
France
Kneider Innovations (shipboard navigation using wave energy)
Tidal Energy Station (tidal barrage), La Rance
Germany
Energy Island (Floating OTEC/wave/wind/solar/current recombinant energy plants)
Ocean Power Plant (Offshore Wind Park- Proposed combined Wind (36MW), OTEC (36MW), Wave (36MW))
Greece
DAEDALUS Informatics (turbines for current, tidal, OWC energy), Athens
Ireland
Hydam Technology Limited (shoreline wave energy), Kerry
duQuesne Environmental Ltd. (nearshore wave energy), Dublin
Netherlands
Neptune Systems (offshore, nearshore tidal current and wave energy)
Archimedes Wave Swing (offshore wave energy)
Norway
Hammerfest Stroem AS (tidal energy), Finmark
Ing. Arvid Nesheim (nearshore wave energy)
Oceanor (offshore wave energy)
Sea Wave Power (offshore, near shore, shoreline wave energy)
Portugal
IST-DEM Instituto Superior Tecnico (near shore wave energy), Lisboa
Spain
Ecological Power Generator (shoreline wave energy)

Table 1 (*Continued*)

Sweden
Sea Power International AB (offshore wave energy)
United Kingdom
Hydroventuri (marine tidal current energy), London
IT Power (marine tidal current energy), Hampshire
Marine Current Turbines, Ltd. (turbines for current, tidal, OWC energy), Hampshire
Ocean Power Delivery Ltd. (offshore wave energy), Scotland
ORECon, Ltd. (Multiple Oscillating Water Column (MOWC) wave energy devices, offshore wave energy), Plymouth
OWEL- Offshore Wave Energy Limited (offshore wave energy), Portsmouth
Robert Gordon University (marine tidal and current energy), Aberdeen, Scotland
School Mechanical Engineering, University of Edinborough (tidal energy), Scotland
The Engineering Business Limited (nearshore tidal energy)
The Wave Power Group (offshore, near shore wave energy), Edinborough, Scotland
Tidal Electric. Ltd. (near shore tidal energy), West Simsbury, CN
Tidal Energy Pty Limited (tidal energy), Queensland, Australia
University of Plymouth (offshore, nearshore wave energy)
Wave Energy Research Team, University of Limerick (Nearshore Wave Energy), Ireland
Wavegen (offshore, nearshore, shoreline wave energy), Northumberland, England

headlands. There are many sites worldwide with current velocities around 2.5 m s^{-1} near the UK, Italy, the Philippines, and Japan. In the United States, the Florida Current and the Gulf Stream are reasonably swift and continuous currents moving close to shore in areas where there is a demand for power. If ocean currents are developed as energy sources, these currents are among the most likely.

1.1. Potential for generating electrical power from the Florida Current

Electrical needs increase over time as population grows. While the number of U.S. households is projected to rise by 1.0% per year between 2000 and 2020, residential demand for electricity is expected to grow by 1.8% annually [6]. This increase in demand of 52% over current capacity over the next 20 years represents a market increase of $17 billion per year. During that same period, the average price of electricity is projected to decline by an average of 0.3% a^{-1} as a result of competition among electricity suppliers. Due to increased demand, approximately 14 GW of new generating capacity will have to be developed in order to keep pace each year. The technological choice for capacity building will be based on least expensive options. Renewable energy sources are projected to remain minor contributors to U.S. electricity supply, increasing from 357×10^9 kWh (an energy expenditure of 1 kWh represents 3,600,000 J viz. 3.600×10^6 J) of generation in 2000 (9% of the total, including co-generation and distributed generation) to 464 billion kWh (9%) in 2020.

The world's largest solar collector (the world ocean) absorbs solar energy equal to 37 trillion kW annually, 4000 times the amount of electricity used by all humans on the planet. A typical square mile of sea surface contains more energy than 7000 barrels of oil. Today, about 90% of the world's power is supplied by fossil fuels and nuclear power. Production and supply of the traditional hydrocarbon fuels (coal, gas and oil) are well established but reserves may peak by the year 2010. Oil and gas reserves are expected to last another century or two, but will begin to diminish within a decade. The world consumes 3 billion gallons of oil a day. Although oil is not a big factor in generating electricity compared to gas and coal, it is a major factor in harmful emissions from transportation systems. This environmental damage could be partly offset by generating electricity from ocean currents. With the increasing cost of oil (about US$55 per barrel), ocean current power becomes an attractive alternative energy source.

1.2. Power demands in Southern Florida

Florida Power and Light (FPL) is the nation's third largest investor-owned electric utility and among the fastest growing. In 2003, the average number of FPL accounts grew by more than 97,000 (2.4% increase) to more than 4.1 million. Florida's increase in population represents more than 11% of the nation's housing starts in 2003. In 2003, Florida's job growth was the highest in the nation and greater than that of the next four highest states combined. The electricity usage by FPL customers, among the highest in the industry, increased 1.7% over the previous year. FPL sells more retail kilowatt-hours than any other utility in the U.S. In 2003, total sales reached an all time high of more than 103 million MWh. Since 1993, FPL has averaged annual total sales growth of 3.6% compared to the most recently reported 10-year industry average of 2.4%.

New technologies offer new possibilities for increasing electricity supply and especially attractive is the potential for extracting power from the ocean. Several conditions must come together for ocean power to be technologically and commercially viable. Obvious, in the first instance, is demand for electricity from a market situated along the coast. In order to generate electricity from ocean currents, there needs to be a relatively fast flowing current near the shore. Of the western boundary currents, which are among the strongest ocean currents, the Florida Current (Gulf Stream) is an obvious choice for the east coast of the United States. The current passes closest to the coast offshore from the Miami–Palm Beach conurbation, thereby providing an ideal opportunity to test the concept of generating electricity from ocean currents.

1.3. Purpose

This paper highlights some salient considerations not only of the technological feasibility, but also of environmental considerations that will constrain development, field-testing, and implementation. First considered is the potential of the Gulf Stream to provide a consistent and renewable flow of water followed by a brief summary discussion of the proposed marine energy production units (EPUs). Paramount in this conceptualization of generating electricity from ocean currents are environmental considerations. Although concerns over implementation of this new technology are legion, numerous task-force investigations have mediated environmental concerns and some of these are briefly indicated here.

The Miami–Palm Beach metropolitan area sits on a coastal plain that fringes a narrow continental shelf that drops off to deeper waters of the Florida Straits, which is about 700 m deep. The strong ocean currents in the Straits have long fascinated oceanographers, geographers, and most recently engineers who dream of harnessing power from the ocean. Expansive growth of this metropolitan area requires energy to support homes, industry, and commercial enterprises that are largely geared to tourism. Meeting these increasing needs, although challenging, have been met by decades-long use of nuclear power-generating plants (*e.g.* Turkey Point,

Hutchinson Island) and upgrades to conventional power-generating plants to clean gas-powered facilities. Continued increases in the coast of oil and gas, combined with environmental concerns over emissions, spur interesting alternative energy sources. Ocean power (tidal, wave energy, OTEC) has long been a dream to obtain sustainable and reliable power generation [5]. Although mostly undeveloped, the realization of substantial use of ocean power remains elusive. Problems associated with biofouling and maintaining mechanical integrity of units in a hostile marine environment have thwarted most previous attempts to secure power from the oceans. The development of new technology coupled with a large urban center on the fringe of a narrow shelf juxtaposed to the fastest flowing ocean current in the world brings together several pieces of a complicated puzzle.

Simple back of the envelope calculations suggest that flow of the Florida Current is sufficient to provide energy for electrical power generation. The speed of the Florida Current (1 m s^{-1}) through a surface of 1 m^2 perpendicular to the flow direction makes a flow of 1 m^3 s^{-1} (1 ton of water per second). A mass of 1 ton of water moving at a velocity of 1 m s^{-1} has a kinetic energy of 500 J ($E_k = 1/2mv^2$). Thus, a watermill of 1 m^2 surface, placed into the flow of the Florida Current, would receive from the water a power of 500 W, that is 1/2 kW ($P = 1/2\rho\,\mathrm{Sv}^2$) ($\rho$ is the density of water: 1000 kg m^{-3}). Assuming a final efficiency of 20%, that makes 100 W/m^2 watermill. Thus, an EPU anchored on the bottom of the ocean will be able to deliver the same power as a conventional power plant. From a theoretical point of view, the potential of ocean current power generation is there. An exciting technology in this regard is the rim-driven turbine developed by Florida Hydro Power and Light Company.

One of the primary advantages of this technology is the energy density. While solar and wind systems are well suited for remote off grid locations, ocean energy is ideal for large-scale developments in the multiple gigawatt range. Seawater is 832 times as dense as air, providing a 5-knot ocean current with more kinetic energy than a 350 km h^{-1} wind.

1.4. Florida Current – Gulf Stream System

The Florida Current can be considered the "official" beginning of the Gulf Stream System. It is usually defined as that section of the system that stretches from the Florida Straits (Fig. 1) northwards to Cape Hatteras. The Florida Current, first reported by the Spanish explorer Ponce de Leon in 1513 when he discovered Florida [7], receives its water from two main sources, the Loop Current and the Antilles Current. The Loop Current is the most significant of these sources and can be considered the upstream extension of the Gulf Stream System.

The Gulf Stream is the western boundary current of the North Atlantic subtropical gyre (Fig. 1). The Gulf Stream transports significant amount of warm water (heat) poleward. The averaging of velocity data from a meandering current produces a wide mean picture of the flow. The core of the Gulf Stream current is about 90 km wide and has peak velocities of greater than 2 m s^{-1}, making it the fastest ocean current in the world. Maximum velocities are confined to the upper 200 m of the water column and decreases with depth where the flow below 1000 m is usually less than 10 cm s^{-1}.

As reported in the historical literature, the Florida Current has a mean transport of about 30 Sv [8,9], a value confirmed in numerous modern studies. A mean transport of 31.5 Sv at 27°N in the Straits of Florida is verified by Molinari et al. [10], Leaman et al. [11], Schott et al. [12], and Larsen and Sanford [13]. Using undersea cables, current meter moorings and a Pegasus profiler, researchers confirmed that all three methods produced transports rates within 1–2 Sv of each other. Seasonal and interannual variability can amount to as much as a 10 Sv difference between high and low values along the eastern Florida coast [12].

The seasonal signal in the Florida Current was discovered in tide gauge measurements by Montgomery [14] who found evidence for a seasonal maximum in July and minimum in October with secondary maximum and minimum in January and April, respectively. Niiler and Richardson [9] found a winter transport

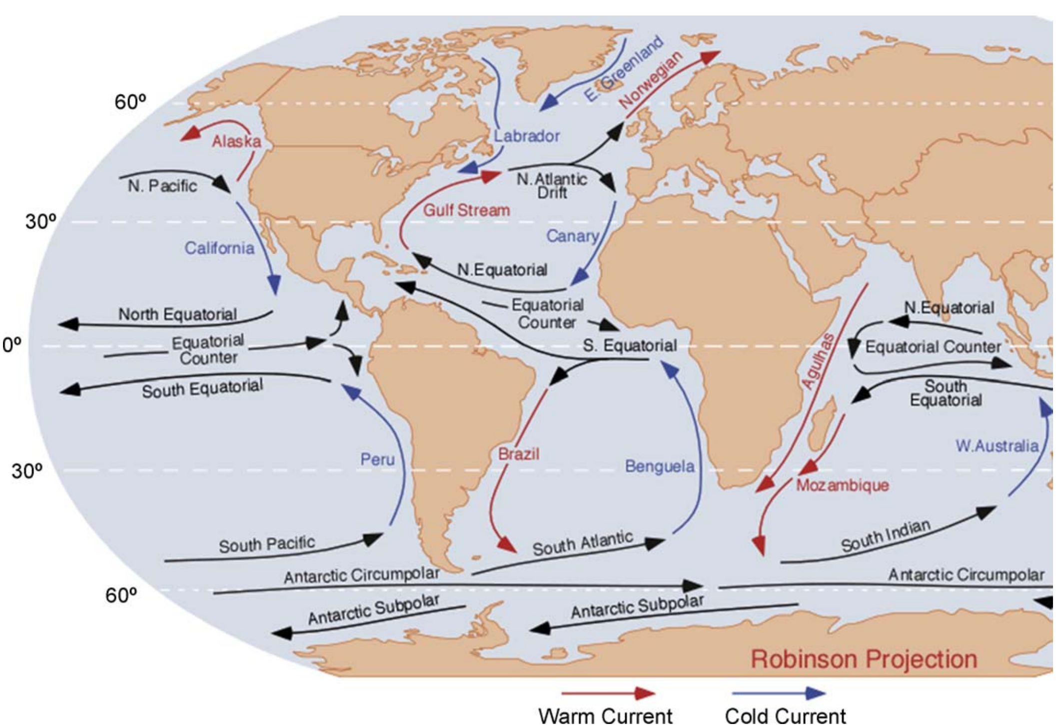

Fig. 1. Portion of major ocean currents focusing on the western North Atlantic Ocean where the Gulf Stream, initiated near the southeast Florida coast as the Florida Current, provides a potential renewable energy source offshore from the Miami–Palm Beach conurbation.

of 25.4 Sv and summer transport of 33.6 Sv and that seasonal changes accounted for about 45% of the variability between historical transport estimates. This supports Wunsch et al. [15] who, based on sea level height differences, concluded that the seasonal transport differences were approximately 10% of the annual mean signal. In addition to the annual signal, there is also a semiannual summer maximum tied to an additional strengthening of the trade winds and increase in local winds [16]. Historical records have shown that monthly variability within the Florida Current can be as high as the seasonal variability. There are also short-term variations with periods of 2–20 days. These fluctuations are correlated to local winds and are much stronger in summer than in winter [16].

2. EPU design capabilities

One Florida Hydro EPU (approximately 45 m in length) is designed to produce approximately 2–3 MW of electricity (Fig. 2). Each EPU is capable of powering about 1500 homes. The units will be installed in groups or clusters to form a marine current farm, with a predicted capacity of up to eight turbines 2.6 km^2 (Fig. 3). This grouping is intended to avoid wake-interaction effects between the turbines and to allow access by maintenance vessels. An 80% capacity factor is targeted, averaging approximately 17,520 MWh per unit per year. It is expected that the overall capacity associated with the project in Palm Beach County, Florida, will be determined by research, which identifies the best number of units and transmission lines to provide power while avoiding significant use conflicts and avoiding impacts on significant environmental resources. The U.S. Navy's Surface Warfare Center's Carderock Division examined the system in 2003 and subsequently agreed to pursue a Cooperative Research and Development Agreement (CRADA) with Florida Hydro to commercialize the technology.

3. Environmental considerations

As development and commercialization of this new technology proceeds, other facets of whether the system can be deployed as envisaged depends on its compatibility with coastal marine environments. The proposed test site and area of eventual implementation of EPU fields in the Florida Current off the southeast coast of Florida sits in a sensitive spot. The area lying on the cusp between the Nearctic and Neotropic terrestrial ecoregion classification areas [19] is adjacent to protected areas defined in the World Database on Protected Areas [17], viz. Florida Keys National Marine Sanctuary and Associated Aquatic Preserves and the Biscayne Bay Aquatic Preserve. With guidance from the United States Coral Reef Task Force, the Florida Department of Environmental Protection and the Florida Fish and Wildlife Conservation Commission have coordinated formation of an interagency Southeast Florida Action Strategy Team (SEFAST) for coral reef conservation and management. This team is developing a local action plan to improve coordination of technical and financial support for the conservation and management of the coral reefs in the Florida Reef Tract. The Southeast Florida Coral Reef Initiative (SEFCRI) is targeting this region because the coral habitats are close to shore and co-exist with intensely urbanized areas that lack a coordinated management plan like that of the Florida Keys National Marine Sanctuary.To date, there is a Particularly Sensitive Sea Area (PSSA) around the Florida Keys, and six other areas outside U.S. territorial waters [18,19]. The designation requires the use of special precautions such as avoiding ecologically vulnerable areas, using vessel traffic monitoring systems, traffic separation schemes, compulsory pilotage, and escort towing of tankers to and from ports. The Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO), which is the UN organization responsible for the worldwide regulation of shipping, has responsibility for designating PSSA. A PSSA needs special protection through action by the IMO because of its significance for recognized ecological or socio-economic or scientific reasons, and which may be vulnerable to damage by international maritime activities.

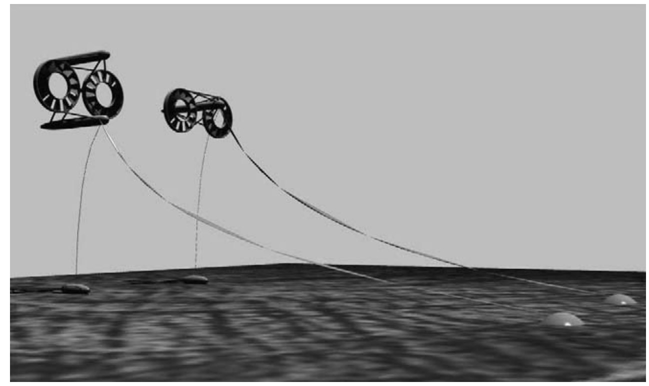

Fig. 3. Panoramic view of Florida Hydro's conception of EPUs that could be tethered to the seafloor in groups to form marine current farms of up to eight turbines spread over about 2.6 km^2.

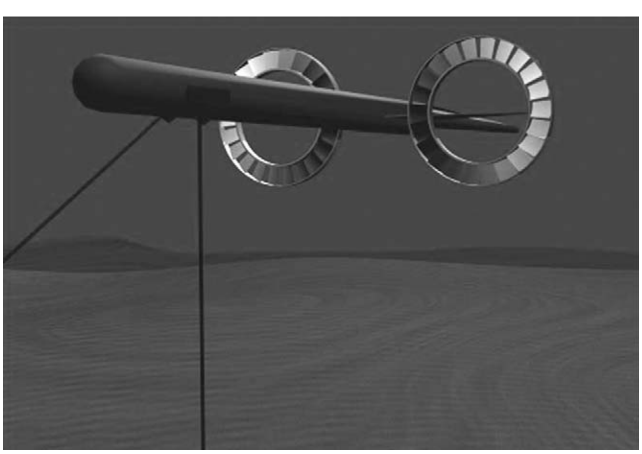

Fig. 2. Close-up perspective view of Florida Hydro's conceptual design for one EPU (energy production unit) that is tethered to the seafloor on adjustable cables to provide repositioning for maintenance service and to maximize capture of high flow velocities.

Many concerns have been separately addressed by the Florida Department of Environmental Protection in relation to the proposed anchoring of mid-water EPUs to the outer continental shelf seafloor with a retention–transmission cable system. Individual transmission cables will be attached to a grid system for transmission of energy to a shore based receiving station. The units, proposed for installation, will lie 3–20 nautical miles offshore of southeast Florida in approximately 100–500 m of water. A ballast tank in the EPU is designed to support the turbine 60 m below the sea surface.

This array of EPUs has the potential to pose numerous problems to pelagic and benthic environments, not the least of which are possible offshore impacts on trawling for shrimp and pot fisheries for crab, migratory routes for large mammals (*e.g.* Sei whale, *Balaenoptera borealis*; Fin whale, *Balaenoptera physalus*; North Atlantic right whale, *Eubalaena glacialis* (*Balaena glacialis* [incl. *Australis*]); Humpback whale, *Megaptera novaeangliae*; Sperm whale, *Physeter macrocephalus*) and turtles (Loggerhead, *Caretta caretta*; Green turtles, *Chelonia mydas*; Leatherback, *Dermochelys coriacea*; Hawksbill, *Eretmochelys imbricate*; Kemp's Ridley, *Lepi-*

dochelys kempii), schooling fish, and sport fisheries. Deepwater environmental concerns are perhaps more easily dealt with than shallow water environments where there is apparently more potential for damage to sensitive coastal marine environments viz. hard and soft corals of the Florida Reef Tract and to soft bottom benthic habitats. Concerns in this area center on methods of bringing subsea transmission cables ashore. Transit up the continental slope and over the shelf break poses relatively minor problems compared to crossing the inner continental shelf where there are protected environments and where there is greater development of coastal infrastructure and commercialization of many coastal marine resources. Potential problems associated with crossing the Florida Reef Tract are solved by a combination of horizontal subsea drilling and passage of cables through reef gaps. The availability of extremely detailed airborne laser bathymetry (ALB) and geomorphological interpretation of bottom types based on this new technology [20] have facilitated the minimization of potential damage to hardbottom resources. Baseline studies will involve benthic surveys, which may include sidescan sonar, sled-mounted video camera, seafloor-mounted ADCPs, and/or remotely operated vehicles (ROV). Sidescan sonar is used to identify hardbottom habitats, cultural resources or other sensitive surficial features. A sled-mounted video cameras help to assess epibenthic communities and, in conjunction with sidescan sonar, to identify unknown objects or anomalies in the images. Current meters are used to evaluate seafloor currents. ROVs are useful for collecting samples or conducting other activities that require deepwater submersibles. Setbacks from sensitive environments such as the FRT and state-of-the-art drilling (*e.g.* HDD or Horizontal Directional Drilling) further reduce potential for damage. These kinds of efforts will be conducted in accordance with the National Environmental Policy Act that requires documentation of project development phases. The scoping process associated with Environmental Assessment (EA), Environmental Impact Statement (EIS), and other federal and/or state review processes are expected to define and initiate studies specific to agency and other stakeholder concerns.

4. EPU risk and vulnerability

Susceptibility of the EPU field to natural hazards such as hurricanes is minimized by the mid-water placement of the EPU and tethering to seafloor anchors. Although other natural phenomena such as tsunamis, subsea storms, earthquakes, and slumps along the continental slope are not known to be prevalent in this region. Greater risk is more likely associated with human activities that might inadvertently come in contact with the EPU field viz. shipping in one of the busiest sea-lanes in the world [21] and an obstacle to submarines. In times when terrorist activities threaten infrastructure on land and in the air, placement of power generation facilities at sea may pose an inviting target to terrorist determined to interrupt electrical power supply. Because of its large footprint, the EPU field would be difficult to protect from sabotage but on the other hand, the wide spacing of EPUs to avoid wakes from upstream units would make it difficult to interfere with a large number of units over a short time span. Trawlers dragging cable-cutting lines, for example, could place large numbers of generating units in harms way.

5. Discussion

As with any new technology, all kinds of concerns are raised [22]. Some concerns are relevant and some are inappropriate because of incomplete understanding of the issue or processes involved. Of all locations in the world, the Straits of Florida offer optimum test conditions for proof of concept. Deployment of open-center turbine technology in the steady fast flow of the Florida Current should test the concept of a marine current farm to harness kinetic energy and convert it into electrical power for consumption by an expanding local market. Grand schemes such as the one proposed by Florida Hydro require investigation on all scales, from the minutest technical detail to mega-environmental considerations. Whatever the scale of observation, technical development, and deployment, there is potential for error or miscalculation. According to Collin [23] there are three forces that continuously operate independently and in concert to produce success or failure. These forces are often referred to a creation, denying, resolving or more simply as Forces 1–3. Creation or Force 1, which results from brainstorms and intuition, is conditioned by Force 2 that acts like a pre-sageing vignette or trailer to a movie. It is in effect a warning of what can go wrong. Failure to be cognizant of Force often results in tragedy or catastrophic failure. In business, the denial stage is sometimes referred to Murphy's Law (whatever can go wrong will go wrong). Most often, Force 2 is empowered by reluctance to spend the time, effort, and funds that are required to properly address potential causes of failure. An example of denial in many marine projects is related to biofouling (a process in which marine organisms like bacteria, mussels, or barnacles, attach to substrates such as ships hulls or other structures), which is often regarded as benign by those unfamiliar with the growth of marine algae and other sessile marine organisms that can attach themselves to almost any kind of surface for a foothold. Marine growth on the hulls of ships causes drag and decreases the efficiency of hull movement through water (Fig. 4). Biofouling could have deleterious effects on the efficiency of the EPUs that require rotation of turbine blades to produce electricity. Biofouling will certainly occur on the turbine blades and some practical method of cleaning must be developed. The operating depths of the EPUs (100–500 m) are beyond practical diver depths for manual cleaning and ROVs would be hampered by the strong currents. Just one example of Force 2 modulation of an ambitious project, there are many other facets of current farming that require resolution before full-scale implementation. Most other environmental issues have been responsibly addressed and can be mitigated by existing methods and procedures, as alluded to in this brief overview. It must be admitted, however, that Force 3 conditions have not been thoroughly investigated or are not even knowable as in the case of resolving the biofouling problem.

Fig. 4. Example of biofouling where marine growth on the hulls of ships causes drag, which may become a problem to turbine blades. Biofouling of the turbine blades would decrease the efficiency of the EPU.

Tapping of currents has been proposed, but not actually considered, in the past. The matter was already discussed at the *Quatrièmes journées de l'Hydraulique* – whose voluminous proceedings were published by *La Houille Blanche* – which came on the

heels of the historical completion of the tidal power plant of the Rance River. The gigantic Coriolis project from Aerovironment, a California firm, also aimed at harnessing *in partim* the Gulf Stream and/or the Florida Current. This project generated both considerable enthusiasm among proponents of putting to work ocean energy and considerable objections from environmental groups who predicted severe biological and dire climatic consequences.

5.1. A brief look back

Hopes of harnessing ocean currents – besides tidal currents – were expressed more than half a century ago. Bouteloup[1] in 1950 and Remenieras[2] in 1950 and in 1957, held that ocean currents could become power providers. Taking into consideration the technology developed by them, they recommended considering only sites that are sheltered or estuarine. About two decades later, von Arx, Stewart and Apel[3] suggested that a cluster of rather large turbines be placed in the Florida Straits, where the Gulf Stream flows. They figured that they would generate, on a year-round basis, about a million kilowatts, or as much as two very large nuclear power plants. The kinetic energy available in the Florida Current is about that produced by twenty-five 1000-MW conventional power plants. Current could provide power for land-based consumers, the Workshop concluded, in any area where fast long-shore marine currents flow. That same year G. Steelman[4] suggested to place an electric generator aboard a ship anchored offshore with a wheel placed below the ship. An umbrella-like equipped cable would catch the current: umbrellas would open when facing the current, close when not facing it.

Already then worries were uttered about navigational hazards and potential climatic changes.

Ocean current energy use was thereafter examined a.o. by Heronemus[5] (1974), Sheets[6] (1975), Richards[7] (1976); Justus[8] (1977) and Morrison[9] (1978). Among the geographical sites considered as potential location, besides the Florida Current-Gulf Stream, are the Straits of Gibraltar, the Bab-el-Mandeb, the canal from the Mediterranean Sea to the Dead Sea and the Qatara Basin. The canal idea came up already 150 years ago and generation of electricity was mentioned in 1902 and in the 1970s. The Qatara projects date back some 80 years. The only recorded actual harnessing of an ocean current is probably that of Breidefjord, Iceland; a small pump was driven by ocean- and tidal-currents. Which of course brings up the matter of putting to work tidal currents: it could be tapped both in the sea environment and in tidal streams, and would be extracted far less expensively than tidal energy (up and down movement) and probably than marine currents.

Using ocean currents to produce "clean" electricity is a topic that has come up with insistence in trade publications during the years 2002–2004, with concrete proposals of P. Fraenkel (*World Energy Review)* [24] whose projects centered on schemes and proposals aimed at the British Isles. But not only the ocean currents are currently on the front burner, interest is also focused on a particular aspect of tidal power; the tidal current. Besides the paper by Charlier [24], there is a relatively recent study by Bryden. There is thus[10] clearly a revival of interest for ocean generated electricity and by no means limited to marine winds, currently a hot market item [25,26].

6. Conclusions

Development and field-testing of power generation from ocean currents, an indirect source of solar energy, are supported by numerous research groups. Conditions required for successful application of this new technology come together along the southeast coast of the Florida Peninsula where the world's fastest flowing current, the Florida Current that eventually turns into the Gulf Stream, flows through the narrow Straits of Florida. Urban expansion and demand for increased electrical supply along this coast provide a ready market for ocean power that could be derived from energy production units that are tethered to the seafloor and arranged in mid-water positions as a energy production field. Crucial to the success of this new concept is installation of Florida Hydro's state-of-the-art open-center turbine technology, an electrical device that was conceived and designed solely for harnessing the kinetic energy from flowing water. This entirely new energy resource is cost competitive with or lower than fossil fuels. The open-center turbine technology is a 'green' energy source because it is the first truly fish-friendly turbine with 100% survivability of fish and marine mammals. Although the turbines themselves are environmentally friendly, extreme care must be used to route transmission lines across the continental shelf to sensitive coastal marine environments of the Florida Reef Tract. Using combinations of trenching, horizontal drilling, and surface passage across coral reefs through reef gaps it should be possible to avoid damage to hard and soft corals. With guidance by the Marine Environment Protection Committee of the International Maritime Organization for a Particularly Sensitive Sea Area in southeast Florida coastal waters, environmental concern is noted and exercised according to national and international industry standards. Environmental concerns take many forms and new potential threats for environmental safety loom on the horizon in the form of terrorist attack or sabotage of the marine current farm comprising clustered EPUs. Notwithstanding all potential concerns (environmental and otherwise), as occur with any new technology, this indirect source of solar power offers realistic opportunities to tap into a renewable energy source at a cost that is competitive or less than present production methods.

[1] Bouteloup, J., 1950. *Vagues, marées, courants marins*: Paris, Presses Universitaires de France.

[2] Remenieras, G.G., Smagghe, P., 1957. Sur la possibilité d'utiliser l'énergie des courants marins au moyen des machines à aérogénérateurs: *IVes Journées de l'Hydraulique;* No. Spécial de la *Houille Blanche* II, pp. 532–539.

[3] Von Arx, W.S., Stewart, H.B.Jr, Apel, J.R., 1974, The Florida Current as a potential source of useable energy. In Stewart, H.B.Jr (Ed.), *Proc. MacArthur Workshop on the Feasibility of Extracting Useable Energy from the Florida Current* [NOAA Atlantic Oceanogr. & Meteorol. Lab., Miami FL], pp. *91–103*.

[4] Steelman, G., 1974. An invention designed to convert ocean currents into useable power. In Stewart, H.B.Jr (Ed.), *Proc. MacArthur Wksh. Feasibil. Extract. Useable En. Fr. Florida Curr.*, pp. 258–277.

[5] Heronemus, W.E., 1974. Using two renewables: *Oceanus* VIII, 3, pp. 20–27.

[6] Sheets, H.E., 1975. Power generation from ocean currents: *Nav. Eng. J.* 87, 2, pp. 47–56.

[7] Richards, A.F., 1976. Extracting energy from the ocean – A review: *Mar. Tech. Soc. J.* 10, 2, pp. 5–24.

[8] Justus, J.R., 1977. Renewable sources of energy from the ocean. In *Project interdependence: US and World energy outlook through 1990: Rep. To Congress, Res. Serv. Lib. Congr.*: Washington DC, US Gov. Print. Off. pp. 121–148.

[9] Morrison, R.E, 1978. Energy from ocean currents – Energy from the ocean: *Rep. Sci. Pol. Div. Congr. Res. Serv. Lib. Congr.:* Washington DC, US Gov. Print. Off. pp. 149–173.

References

[1] Finkl CW. Le frontiere delle technologia, Jacques Cousteau Planeta Mare (Enciclopedia di Scienza e di Avventura). Gruppo Editoriale Fabbri Milano 1980;2(5):65–80.
[2] Charlier RH. Tidal energy. New York: Van Nostrand Reinhold; 1982. p. 351.
[3] Charlier RH. Sustainable co-generation from the tides: bibliography. Renewable Sustainable Energy Rev 2003;7(2003):215–47.
[4] Charlier RH. Sustainable co-generation from the tides: a review. Renewable Sustainable Energy Rev 2003;7(2003):187–213.
[5] Charlier RH, Justus JR. Ocean energies—environmental, economic and technical aspects of alternative power sources. Amsterdam: Elsevier Oceanography Series; 1993. p. 534.

[6] U.S. Department of Energy, Energy Information Administration. Annual energy outlook 2002 with projections to 2020, report no. DOE/EIA-0383 (2002); December 21, 2001.
[7] Galstoff PS. Historical sketch of the explorations in the Gulf of Mexico. In: Galstoff PS, editor. Gulf of Mexico and its origin, waters, and marine life, vol. 55. Fishery Bulletin of the Fish and Wildlife Service; 1954. p. 3–36.
[8] Schmitz Jr WJ, Richardson WS. On the transport of the Florida current. Deep-Sea Res 1968;15:679–93.
[9] Niiler PP, Richardson WS. Seasonal variability of the Florida current. J Mar Res 1973;31:144–67.
[10] Molinari RL, Wilson WD, Leaman K. Volume and heat transports of the Florida current: April 1982 through August 1983. Science 1985;227:292–4.
[11] Leaman KD, Molinari R, Vertes P. Structure and variability of the Florida current at 27N: April 1982–July 1984. J Phys Oceanogr 1987;17:565–83.
[12] Schott F, Lee TN, Zantopp R. Variability of structure and transport of the Florida current in the period range of days to seasonal. J Phys Oceanogr 1988; 18:1209–30.
[13] Larsen JC, Sanford TB. Florida current volume transport from voltage measurements. Science 1985;227:302–4.
[14] Montgomery RB. Fluctuations in the monthly sea level on the Eastern U.S. coast as related to dynamics of the western North Atlantic Ocean. J Mar Res 1938;1:32–7.
[15] Wunsch C, Hansen DV, Zetler BD. Fluctuations of the Florida current inferred from sea level records. Deep-Sea Res 1969;16(Suppl.):447–70.
[16] Lee TN, Williams E. Wind-forced transport fluctuations of the Florida current. J Phys Oceanogr 1988;18:937–46.
[17] World Database on Protected Areas Consortium. 2003 world database on protected areas, 27 October 2004, (http://www.gis.tnc.org/data/IMS/WDPA_-viewer/WDPA_info/DC_datalayers.html); 2003.
[18] Brooks TM, Bakarr MI, Boucher T, do Fonseca GAB, Hilton-Taylor C, Hoekstra JM, et al. Coverage provided by the global protected area system: is it enough? BioScience 2005;54(12):1081–91.
[19] Olson DM, Dinerstein E, Wikramanayake ED, Burgess ND, Powell GVN, Underwood EC, et al. Terrestrial ecoregions of the world: a new map of life on earth. BioScience 2001;51:933–8.
[20] Finkl CW, Benedet L, Andrews JL. Laser airborne depth sounder (lads): a new bathymetric survey technique in the service of coastal engineering, environmental studies, and coastal zone management. In: Proceedings of the 17th annual national conference on beach preservation technology, 11–13 February 2004, Lake Buena Vista, Florida, Florida Shore & Beach Preservation Association, Tallahassee, Florida, CD-ROM; 2004. p. 15.
[21] Finkl CW. Le strada del mare, Jacques Cousteau Planeta Mare (Enciclopedia di Scienza e di Avventura). Gruppo Editoriale Fabbri Milano 1980;1(4):81–96.
[22] Morcos S, Zhu M, Charlier RH, et al., editors. Ocean sciences bridging the Millennium. A spectrum of historical accounts: UNESCO-IOC. Paris & Qingdao: China Ocean Press; 2004. p. 314–20.
[23] Collin R. The theory of celestial influence. London: Watkins; 1980. p. 391.
[24] Charlier RH, 2003. A ‘‘sleeper’’ awakes: tidal current power. Renewable Sustainable Energy Rev 2003;7:515–29; cf. Symposium on tidal power, proceedings bedford institute of oceanography, Dartmouth, Nova Scotia, Canada; 1984; McArthur Workshop, Miami, Florida; 1974; Fraenkel, P. Energy from the ocean ready to go on steam. Renewable Energy World 2002;8:223–7.
[25] Finkl, CW, Charlier, R, Hague, E., 2005. Some environmental considerations of electrical power generation from ocean currents in the Straits of Florida. Presented to American Society of Mechanical Engineers, 2005 International Solar Energy Conference (6–12 August, Orlando, Florida).
[26] Charlier R, Finkl CW. Ocean Energy: Tide and Tidal Power. Berlin: Springer-Verlag; 2009, 262p.